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Development of a thermoeconomic methodology for optimizing biodiesel production. Part II: Manufacture exergetic cost and biodiesel production cost incorporating carbon credits, a Brazilian case study

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ABSTRACT

The purpose of this study is to carry on a thermoeconomic analysis at a biodiesel production plant considering the irreversibilities in each step (part I: biodiesel plant under study and functional thermoeconomic diagram [1]), making it possible to calculate the thermoeconomic cost in US$/kWh and US$/l of the biodiesel production, and the main byproduct generated, glycerin, incorporating the credits for the CO_2 that is not emitted into the atmosphere (carbon credits). Assuming a sale price for both the biodiesel and the byproduct (glycerin), the annual revenue of the total investment in a plant with a capacity of 8000 t/year of biodiesel operating at 8000 h/year was calculated. The variables that directly or indirectly influence the final thermoeconomic cost include total annual biodiesel production, hours of operation, manufacturing exergy cost, molar ratio in the transesterification reaction, reaction temperature and pressure in the process. Depending on the increase or decrease in sale prices for both biodiesel and glycerin, the payback is going to significantly increase or decrease. It is evident that, in exergy terms, the sale of glycerin is of vital importance in order to reduce the biodiesel price, getting a shorter payback period for the plant under study.

Contents

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Nomenclature

AR	Annual revenue
C_{AC}	Auxiliary costs [US$]
C_{BIO}	Cost of the biodiesel produced [US$/kg], [US$/kWh]
C_{BM}	Total cost of the single module [US$]
$C_{CAT\ IMP}$	Cost of the Catalyst [US$]
C_{CF}	Value of contingency [US$]
$C_{CO_2C\ C}$	Cost of the CO_2 as carbon credits [US$]
C_{EL}	Cost of the electrical energy used by the process [US$]
C_{FC}	Fixed capital costs [US$]
C_{GLY}	Cost of the glycerin produced [US$/kg], [US$/kWh]
$C_{MET\ IMP}$	Cost of methanol as an input [US$/year]
MEC (CM_{ex})	Manufacture Exergetic cost [US$/h]
$C_{O\ M\ A}$	Maintenance, operational and administrative cost [US $/year]
$C_{OIL\ IMP}$	Cost of vegetable oil as an input [US$/year]
C_{TC}	Total investment costs [US$]
C_{TM}	Total cost of the module [US$]
C_{UTIL}	Utility costs (electricity and vapor) [US$]
C_S	Cost of steam consumed in the process [US$]
H	Annual hours of operation [h/year]
I_{BIO}	Biodiesel plant investment [US$]
I_{GLY}	Glycerin production investment [US$]
K	Amortization period [years]
PV_{BIO}	Biodiesel selling price [US$/kg]
PV_{GLY}	Glycerin selling price [US$/kg]
R	Annual interest rate,%
Y	Incremental function in exergetic basis [kW]
$Y_{i,j}$	j-th input to the i-th unit [kW]
$Y_{i,k}$	k-th output of the i-th unit [kW]

1. Introduction

In the second part, a methodology based on the use of thermoeconomic functional diagrams applied in allocating costs of products produced at the biodiesel plant was developed. For a better understanding, it is recommended to conduct a review of the first part of this research which was published in this journal [1].

Basically, an algebraic method based on the combination of the cost analysis with was developed, suggested by Silveira [2,3], with an exergy analysis incorporating the costs of carbon credits for the CO_2 that is not released into the atmosphere when mixing a percentage of biodiesel with regular diesel, which is used by the internal fleet of diesel vehicles in Brazil. The methodology is based on identifying the functions of the system as a whole, and of each unit individually. The construction of the thermoeconomic functional diagram and the formulation of the problem for production cost of biodiesel and related products is presented in this paper. The decision parameter is called the Manufacture Exergetic Cost (MEC).

In scientific literature, there are other methodologies using the thermoeconomic analysis, mainly for thermal systems, combined cycle plants, steel production process, refineries or cogeneration systems [4–9], but as aforementioned in the first part of this research [1], there are few proposals for biofuels, especially biodiesel, however.

On the structure of the second part of the investigation, the investments and manufacture costs of the biodiesel production plant were firstly defined; secondly, the carbon credits on biodiesel production were calculated; thirdly, it was determined the Manufacture Exergetic Cost – MEC; fourthly, scenarios were evaluated in order to show how it affected the price of biodiesel and glycerin by changing the plant's operation hours, the annual production and the molar ratio in the transesterification process. Finally, the annual revenue was calculated according to the sale price of the produced glycerin.

Table 1
Cost of equipment and total capital investment cost in the plant under study. 8000 t/year and 8000 h of operation, [Zhang et al., 2003].

Plant equipment	Cost (US$)
Transesterification unit	290 000
Methanol distillation	140 000
Wash column	100 000
Biodiesel purification	157 000
Glycerin purification	920 00
Neutralization	21 000
Heat exchanger	4 000
Pumps	45 000
Others (Vacuum system, etc.)	46 000
Elemental module cost, C_{BM0}	610 000
Total cost of the simple module, C_{BM}	**810 000**
Contingency fee, C_{CF}=0.18 C_{BM}	145 800
Total cost of the module, $C_{TM}=C_{BM}+C_{CF}$	955 800
Ancillary facility costs, $C_{AC}=0.3C_{BM0}$	183 000
Fixed capital cost, $C_{FC}=C_{TM}+C_{AC}$	1 138 800
Working capital, $C_{WC}=0.15C_{FC}$	170 820
Total Investment Cost $C_{TC}=C_{FC}+C_{WC}$	**1 309 620**
Investment of Biodiesel production, $\boldsymbol{I_{BIO}}$	1 281 620
Investment of Glycerin production, $\boldsymbol{I_{GLI}}$	28 000

2. Investments and manufacturing costs of the biodiesel production plant

Adopting the costs of Zhang [10], Table 1 presents the main investment costs of the plant. The fixed capital cost includes three parts the total cost of the single module, contingencies and ancillary costs. The module cost is a simple sum of each equipment cost in the process. Contingencies are defined as a fraction of the cost of the simple module (18%) in order to cover unforeseen circumstances. Ancillary costs include land purchase, electrical and sanitary installations. Consequently, the total investment cost includes the working capital (15% of the fixed capital cost), [10] and not only but also the total cost of manufacturing refers to the plant operation cost, and is usually divided into three categories: direct costs, manufacturing indirect costs, and overhead costs. The direct costs are raw material costs – consumables, catalysts, solvents, operation, supervision, maintenance, quality control, among others, while the indirect costs are expenses, storage, rent, insurance, and others. The overhead costs are administrative costs, distribution, sale, research and development [10]. Table 2 shows a summary of key operational costs and input prices. The input costs are directly related to the mass flow required for each of the chemicals used in producing biodiesel.

3. Carbon credits on biodiesel production ($C_{CO_2(C.C)}$)

The CDM – Clean Development Mechanism – established in Article 12 of the Kyoto Protocol is an instrument that seeks

Table 2
Raw material costs and operating costs. 8000 t/year [Zhang et al., 2003].

Description of input costs	(US$/year)
Vegetable oil ($C_{OLEO\ INS}$)[a]	8 421 050
Vegetable oil (Zhang et al., 2003[b])	4 200 000
Methanol ($C_{MET\ INS}$)[b]	484 700
Methanol ($C_{MET\ INS}$) (Zhang et al., 2003[b])	170 000
Catalyst ($C_{CAT\ INS}$)	320 000
Utilities, $C_{UTIL}=C_v+C_{EL}$	128 000
Operation cost	580 000
Maintenance cost (6% de C_{FC})	70 000
Administrative costs (25% de overhead)[c]	1 130 000

[a] Prices quoted in the Brazilian market in 2008 [Revista Biodiesel, 2008].
[b] Prices quoted in the Brazilian market in 2008 [Revista Biodiesel, 2008].
[c] Administrative costs include distribution costs, research and development.

reducing greenhouse gas emissions, blamed as the main responsible for the global warming and a contribution to sustainable development in developing countries.

From the CDM, developing countries have become targets of investment for those who need to meet the desired goals for reducing CO_2 emissions. These investments can be made in afforestation and/or reforestation, pictured as carbon sequestration and emission reduction projects, such as planting canola, sunflower, etc.

Each tonne of sequestered or no longer emitted carbon is counted as carbon credits that can be acquired by countries with reduction targets to be reached, thus creating a market for CERs – Certified Emission Reductions. This mechanism is viewed as an alternative investment to reduce the cost of biodiesel produced in plants. Biodiesel production can easily enter the market as a certified emission reduction, since it is known that, if it is added to diesel oil, it will reduce CO_2 emissions, thus generating carbon credits. These credits can be traded with countries that need to meet desired goals for reduction. Each tonne of carbon that is no longer emitted into the atmosphere is sold for prices ranging from US$ 5 to 33.

To estimate the cost of biodiesel from the thermoeconomic analysis, the cost of CO_2 that is left to be released into the atmosphere from the diesel vehicle fleet in Brazil [11] is reflected into carbon credits for the market of CERs that will also be accounted.

4. Methodology

4.1. Determining the manufacture exergetic cost – MEC

The determination of this cost is achieved through the structural model based on costs, associated with manufacturing on an exergetic basis. Fig. 1 lists the allocated costs, according to the unit component of the system as a whole. MEC is formed mainly by input costs of the plant, operation cost, maintenance cost, utilities cost (cost of electricity and steam used in the process) and administrative costs. This cost will also be influenced by the sale of glycerin (donation) and the cost of CO_2 gained from carbon credits reflected in the cost of biodiesel. The steam is used primarily in the transesterification reaction tank as thermal energy to reach the reaction temperature and by the flash chambers for the metahnol recovery. According to the costs diagram (Fig. 1), the MEC can be defined as follows:

$$CM_{ex}=C_{BIO}Y_{12.3}+C_{GLY}Y_{14.2} \tag{1}$$

The main product to be generated in this plant is biodiesel. Glycerin is a byproduct that can be sold, donated or burned up in the case of using its energetic content. To calculate the annual revenue, the sale price will take into account whether the glycerin was sold or not, and its consequences on the payback of the plant under study. In order to reallocate the costs of production for both biodiesel and glycerin, and considering that the only purpose of the plant under study is to produce biodiesel (glycerin is a byproduct that can be sold or not), the following formulas are used to calculate the cost of biodiesel and glycerin. Considering the following weighting factors:

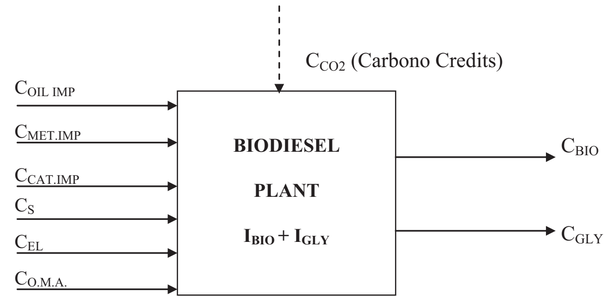

Fig. 1. Structural model based on costs for biodiesel plant.

$$FP_{BIO}=\frac{Y_{12.3}}{Y_{12.3}+Y_{14.2}} \tag{2}$$

$$FP_{GLY}=\frac{Y_{14.2}}{Y_{12.3}+Y_{14.2}} \tag{3}$$

$$C_{BIO}=\frac{I_{BIO}f}{HY_{12.3}}+\frac{C_{MET\ IMP}}{HY_{12.3}}+\frac{C_{CAT\ IMP}}{HY_{12.3}}+\frac{C_{OIL\ IMP}}{HY_{12.3}}+\left(\frac{C_S}{HY_{12.3}}\right)FP_{BIO}+\left(\frac{C_{EL}}{HY_{12.3}}\right)FP_{BIO}+\left(\frac{C_{O\ M\ A}}{HY_{12.3}}\right)FP_{BIO}-\frac{C_{CO_2(C\ C)}}{H.Y_{12.3}} \tag{4}$$

$$C_{GLI}=\frac{I_{GLY}f}{HY_{14.2}}+\left(\frac{C_S}{HY_{14.2}}\right)FP_{GLY}+\left(\frac{C_{EL}}{HY_{14.2}}\right)FP_{GLY}+\left(\frac{C_{O\ M\ A}}{HY_{14.2}}\right)FP_{GLY} \tag{5}$$

The cost $C_{CO_2(C\ C)}$ is only considered for calculating the biodiesel cost, since it is only responsible for reducing CO_2 emissions when used as an alternative fuel in blends with regular diesel. This cost is directly reflected from the ICE diesel vehicle fleet in Brazil that uses only 8000 t of biodiesel produced at the plant under study. For the cost of glycerin (considered as a byproduct), this value is calculated from the cost of purifying glycerin and neutralizer, $[I_{GLY}]$. To calculate the annuity factor, the following equations were used:

$$f=\frac{q^k(q-1)}{q^k-1} \tag{6}$$

$$q=1+\frac{r}{100} \tag{7}$$

The biodiesel, glycerin and the MEC are calculated based on a production of 8000 t/year of biodiesel with 8000 h of operation. The molar ratio of transesterification process is going to remain the same (6:1), the reaction pressure is 400 kPa and the reaction temperature is 60 °C. The MEC was calculated without considering the sale of glycerin on the market.

To calculate the cost of $C_{CO_2(C\ C)}$ (carbon credits), the tons of CO_2 that are not emitted into the atmosphere when biodiesel is added to regular diesel was considered. These calculations were made and demonstrated by Coronado [11]. Taking into account the calculations of CO_2 emissions for the vehicular fleet in Brazil, these vehicles emitted 16,608,000 t of CO_2/year into the atmosphere in 2008, if the regular diesel were replaced by the conventional diesel B5 (5% biodiesel in the mixture) in the energy fuels matrix, the emissions would be reduced to 16.181 million tons CO_2/year [11], which implies in a reduction of 427 000 t CO_2

per year. Each ton of carbon that is no longer emitted in the atmosphere is commercialized in the carbon credits market. If a sale price of 20 US$/ton CO_2 were adopted, this would imply in 6.8 million US$ per year.

In 2008, 44,763,952 m^3 of diesel oil was produced in Brazil [12] where 75% of it was used by the internal diesel fleet. This is about 33,572,964 m^3 of diesel oil for that year. If the diesel vehicle fleet had begun to use the B5 blend in that year, the biodiesel production would have been 1,678,648 m^3, whereas the production of biodiesel plant under study was of 8000 t/year (9111 m^3/year). This would mean that the cost of CO_2 that was not emitted by the use of biodiesel produced in the plant in question would be about 46,352 US$ per year. Considering the average consumption of diesel vehicles in Brazil, the 8000 t of biodiesel produced in the plant would be consumed by about 760 vehicles a year.

The results of the cost of biodiesel, glycerin and the MEC are shown in Table 3, and Figs. 2–4. In Fig. 5, it was chosen an amortization period of 2 years as an example. In order to make a comparison between the methodologies used to calculate the cost of biodiesel produced by Zhang [10] and the present study, Zhang published a biodiesel cost of 0.86 US$/kg. In this study, by applying the thermoeconomic methodology, incorporating costs of carbon

Table 3
Cost of biodiesel and glycerin produced. Density of biodiesel (0.878 kg/l). 1 US $=1.9 R$ (Brazilian Real) – Rel 6:1, 8000 t/year e 8000 h/year. (Density of glycerin=1.2613 kg/l).

r (%)	q	F	C_{BIO} ($/kWh)	C_{BIO} (R$/l)	C_{GLY} ($/kWh)	C_{GLY} ($/l)	$C.M_{EX}$ (US$/h)
***k*=2 years**							
4	1.04	0.5302	0.1327	2.2752	0.0238	0.1587	1472.72
8	1.08	0.5608	0.1331	2.2828	0.0240	0.1600	1477.73
12	1.12	0.5917	0.1336	2.2905	0.0242	0.1606	1482.79
16	1.16	0.6230	0.1341	2.2984	0.0244	0.1622	1487.91
***k*=4 years**							
4	1.04	0.2755	0.1290	2.2116	0.0223	0.1484	1431.03
8	1.08	0.3019	0.1294	2.2182	0.0225	0.1494	1435.35
12	1.12	0.3292	0.1298	2.2250	0.0226	0.1500	1439.83
16	1.16	0.3574	0.1302	2.2320	0.0228	0.1514	1444.43
***k*=6 years**							
4	1.04	0.1908	0.1278	2.1904	0.0218	0.1449	1417.16
8	1.08	0.2163	0.1281	2.1968	0.0219	0.1460	1421.34
12	1.12	0.2432	0.1285	2.2035	0.0221	0.1465	1425.75
16	1.16	0.2714	0.1289	2.2105	0.0223	0.1479	1430.36
***k*=8 years**							
4	1.04	0.1485	0.1271	2.1798	0.0215	0.1432	1410.24
8	1.08	0.1740	0.1275	2.1862	0.0217	0.1442	1414.42
12	1.12	0.2013	0.1279	2.1930	0.0218	0.1448	1418.88
16	1.16	0.2302	0.1283	2.2002	0.0220	0.1462	1423.62
***k*=10 years**							
4	1.04	0.1233	0.1268	2.1735	0.0214	0.1422	1406.11
8	1.08	0.1490	0.1271	2.1800	0.0215	0.1432	1410.33
12	1.12	0.1770	0.1276	2.1869	0.0217	0.1438	1414.90
16	1.16	0.2069	0.1280	2.1944	0.0219	0.1453	1419.80

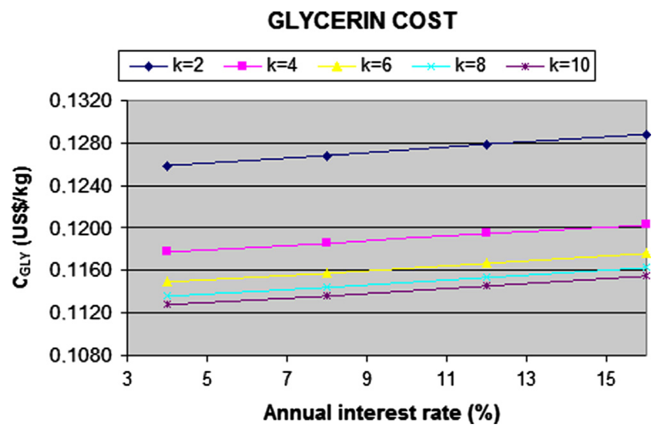

Fig. 3. Cost of glycerin production.

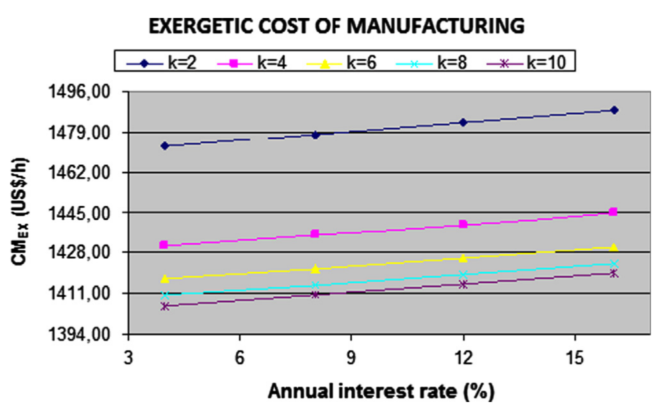

Fig. 4. Manufacture Exergetic Cost (without considering the sale of glycerin). (20 US$/ton CO_2).

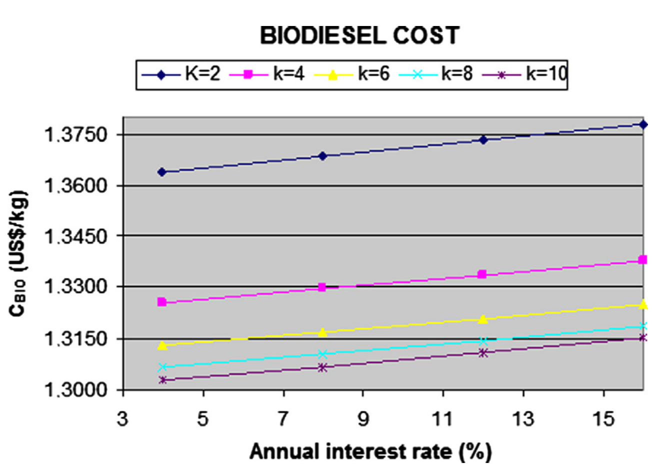

Fig. 2. Cost of biodiesel production, (20 US$/ton CO_2).

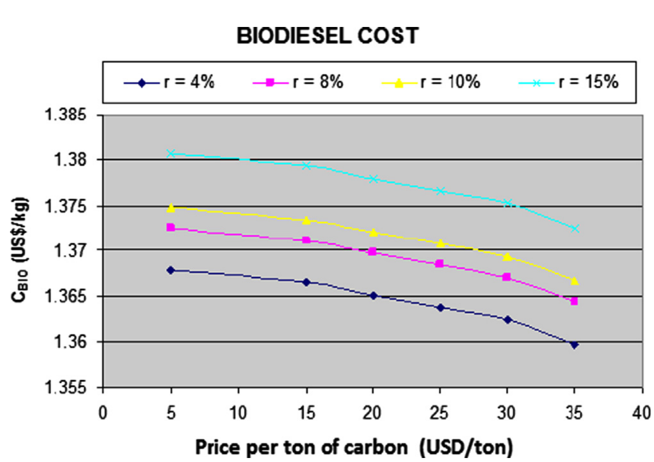

Fig. 5. Cost of biodiesel production by varying the price per ton of CO_2 (k=2 years).

credits and taking into account the costs of Zhang, a value of 0.93 US$/kg was found. As way of comparison, some authors reported biodiesel production costs whose values are similar to those found by Zhang, such as 1.006 US$/kg (using castor oil) [13], 1.014 US$/kg from vegetable oil feedstock [14], and other two authors [15,16] reported similar results. In all cases, the cost of biodiesel calculated in this research from its thermoeconomic analysis is similar. The value slightly differs from the one calculated by [10,13–16] due to the exergetic cost calculated in this study that takes into account all irreversibilities of the system.

On the other hand, the prices of inputs considered for this study (prices quoted in the Brazilian market), both vegetable oil (canola) and methanol considerably differ from the European market (prices quoted by Zhang [10]). The prices of both biodiesel and glycerin for the present study are calculated using the Brazilian market quotations (methanol and vegetable oil). All the other the costs were the same as those used by Zhang [10].

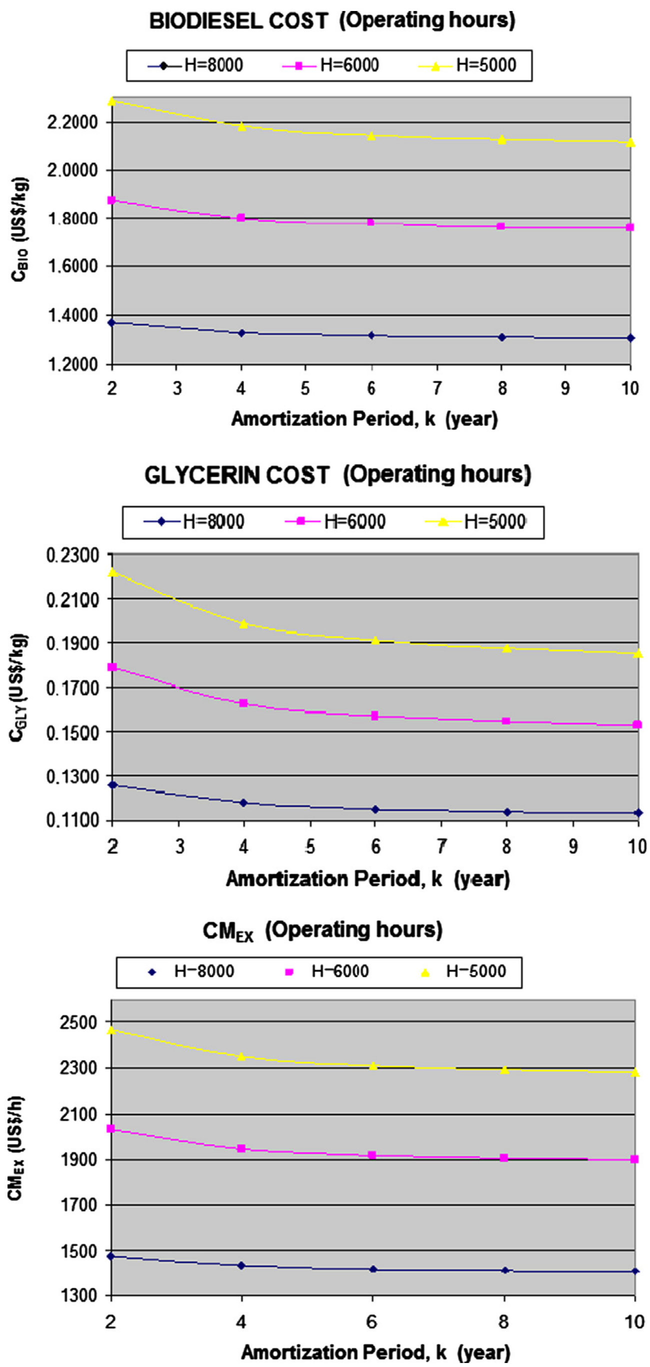

Fig. 6. Cost of biodiesel, glycerin and manufacturing production by varying operating hours. (20 US$/ton CO_2).

4.2. Scenarios

The following part will assess a range of scenarios in order to show how it affected the price of biodiesel and glycerin by changing the following items hours of operation of the plant, annual production and the molar ratio in the transesterification process. Another variable that may influence the final cost of biodiesel and glycerin is the temperature of the reaction process, but it was found that the variation in product costs and MEC as a function of temperature is quite negligible. The difference is most obvious as regards the degree of irreversibility of the process as a whole.

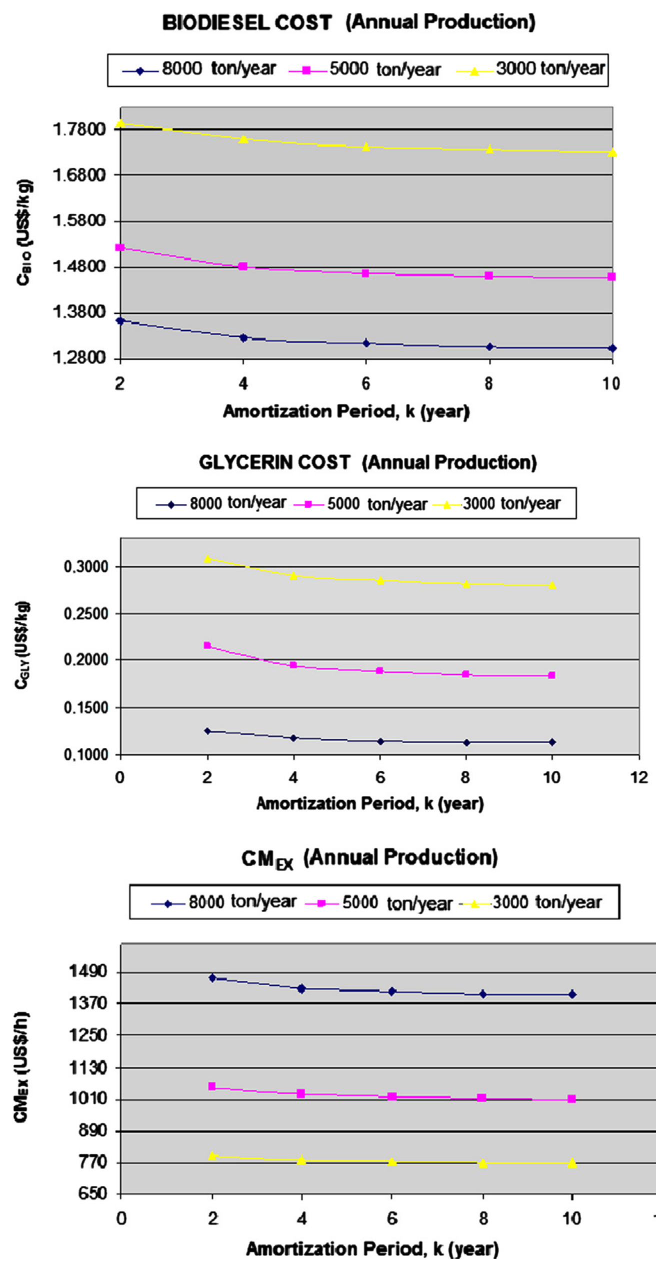

Fig. 7. Cost of biodiesel, glycerin production and manufacturing by varying the total production per year. (20 US$/ton CO_2).

4.2.1. *Hours of operation*

The variables were 8000, 6000 and 5000 h of operation per year, and the constants were annual interest rate of 4%, 6:1 M ratio, reaction temperature of 60 °C and a total production of 8000 t/year. It is noteworthy that the total investment cost varies according to the number of hours of operation, the fewer hours it operates, the greater the investment becomes. The results are shown in Fig. 6.

4.2.2. *Total annual production*

The variables were 8000, 5000 and 3000 t of annual production of biodiesel and the constants were an annual rate of interest of 4%, 6:1 M ratio, a reaction temperature of 60 °C with 8000 h of operation per year. It is noteworthy that a lower production means a lower annual input in the process. When a production of 8000 t/year of biodiesel is considered, the cost of vegetable oil was 8.42×10^6 US$/year. In case of methanol, the cost was 0.48×10^6 US$/year. In the case of a production of 5000 t/year, the cost of vegetable oil was 5.37×10^6 US$/year, and the cost of methanol was 0.41×10^6 US$/year. In the case of a 3000 t/year production, the cost of vegetable oil was 3.53×10^6 US$/year and the cost of methanol was 0.34×10^6 US$/year. Finally, it is noteworthy that a

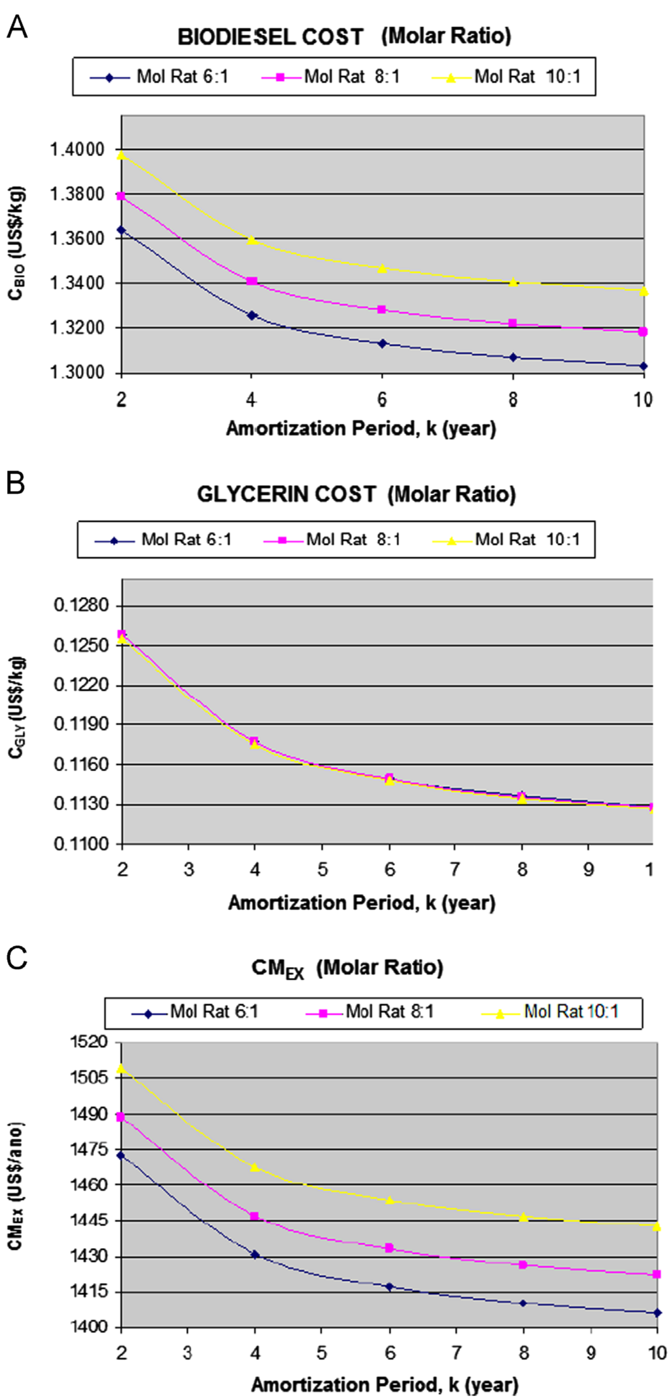

Fig. 8. Cost of biodiesel, glycerin production and manufacturing by varying the molar ratio in the process. (20 US$/ton CO_2).

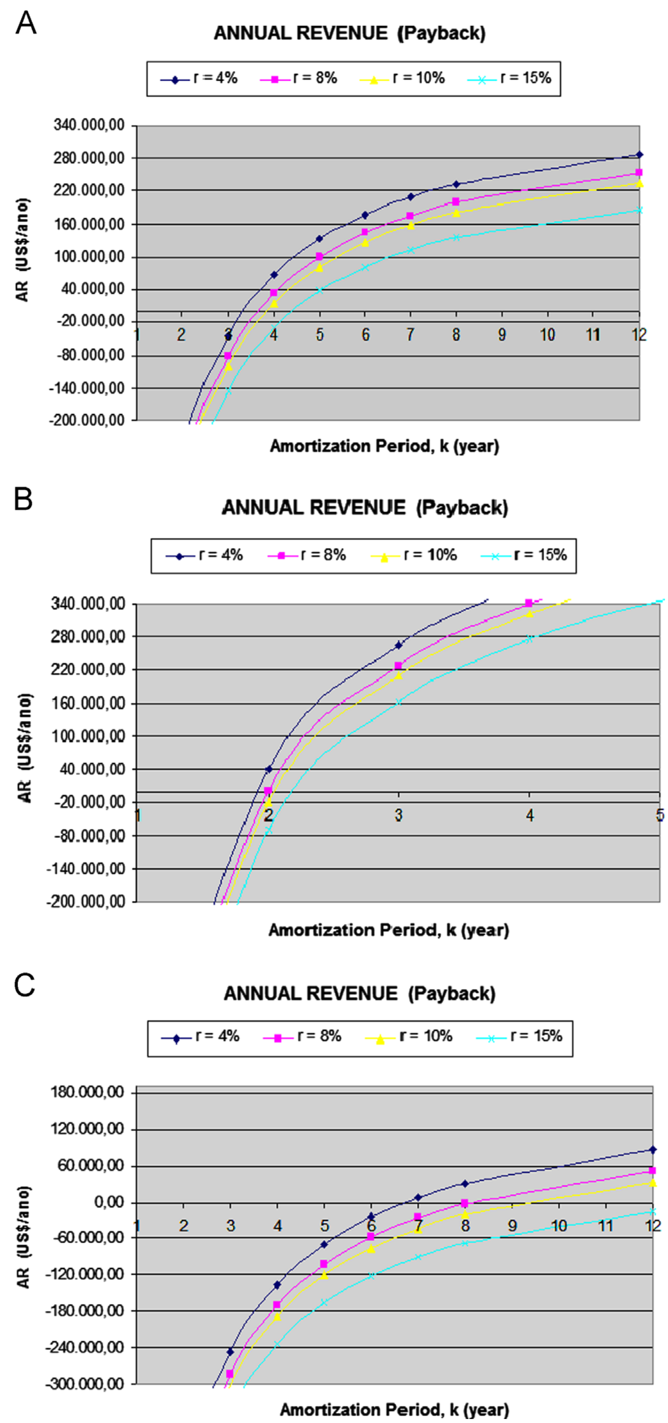

Fig. 9. Annual revenue (molar ratio 6:1, 8000 t/year, 8000 h/year). (R$ = Brazilian Real), 1US$ = 1.9 R$. A: PV_{BIO} = 2.074 R$/liter (1.09 USD/liter), PV_{GLY} = 2.0 R$/kg (1.05 US$/kg). B: PV_{BIO} = 2.13 R$/liter (1.12 US$/liter), PV_{GLY} = 2.0 R$/kg (1.05 US$/kg). C: PV_{BIO} = 2.035 R$/liter (1.071 US$/liter), PV_{GLY} = 2.0 R$/kg (1.05 US$/kg).

low production means a decrease in the plant's investments. The results are shown in Fig. 7.

4.2.3. The molar ratio of the proccess

The variables were 6:1, 8:1 and 10:1 M ratio of methanol:oil in the process. The constants were an annual rate of interest of 4%, a reaction temperature of 60 °C and a total production of 8000 t/year with 8000 hours of operation. The results are presented in Fig. 8. Another variable that could influence the final cost of biodiesel and glycerin is the reaction temperature process, but it was verified that the variation in cost of products and the MEC as a function of temperature is quite insignificant which makes the difference of the irreversibility degree of the process as a whole more evident.

5. Results

To calculate the exergetic increments and the physical exergy flows at each step, the chemical simulation software HYSYS 3.2 was used, since the calculations of chemical exergy were attained based on thermodynamics scientific literature. Through an exergy calculation, it was found that the lower irreversibility of the system refers to the process with a molar ratio of 6:1, with a reaction temperature of 60 °C in the transesterification process.

As aforementioned, the economic viability of a biodiesel plant will largely depend on the sale price of biodiesel and the possible sale price of glycerin, as well. Depending on these prices, either the revenue or the payback on the investment of the plant could be calculated. The selling price of biodiesel would be at first similar to, or lower than the selling price of regular diesel to promote the consumption of biodiesel. In the case of glycerin, it was observed that the selling price of this byproduct decreased from 1.5 US$/kg in 1997 to approximately 1.0 US$/kg in 2009 [17].

For the annual revenue calculation, a selling price of biodiesel (PV_{BIO}) of 0.121 US$/kWh (1.1 US$/liter) was considered which is a similar value to the selling price of diesel at fuel stations in the metropolitan region of southeastern Brazil [18], while for the selling price of glycerin (PV_{GLI}), a value of 0.2 US$/kWh (1.1 US $/kg) was considered. Figs. 9–11 present the payback time

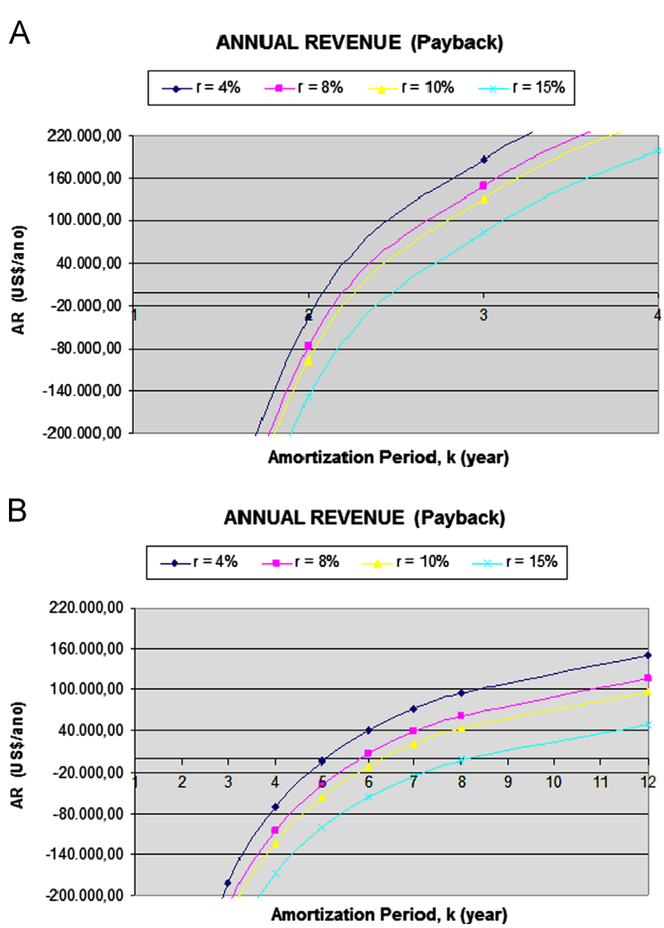

Fig. 10. Annual revenue (molar ratio 6:1, 8000 t/year, 8000 h/year). A: PV_{BIO}=2.074 R$/liter (1.09 US$/liter), PV_{GLY}=2.5 R$/kg (1.32 US$/kg). B: PV_{BIO}=2.074 R$/liter (1.09 US$/liter), PV_{GLY}=1.70 R$/kg (0.89 US$/kg).

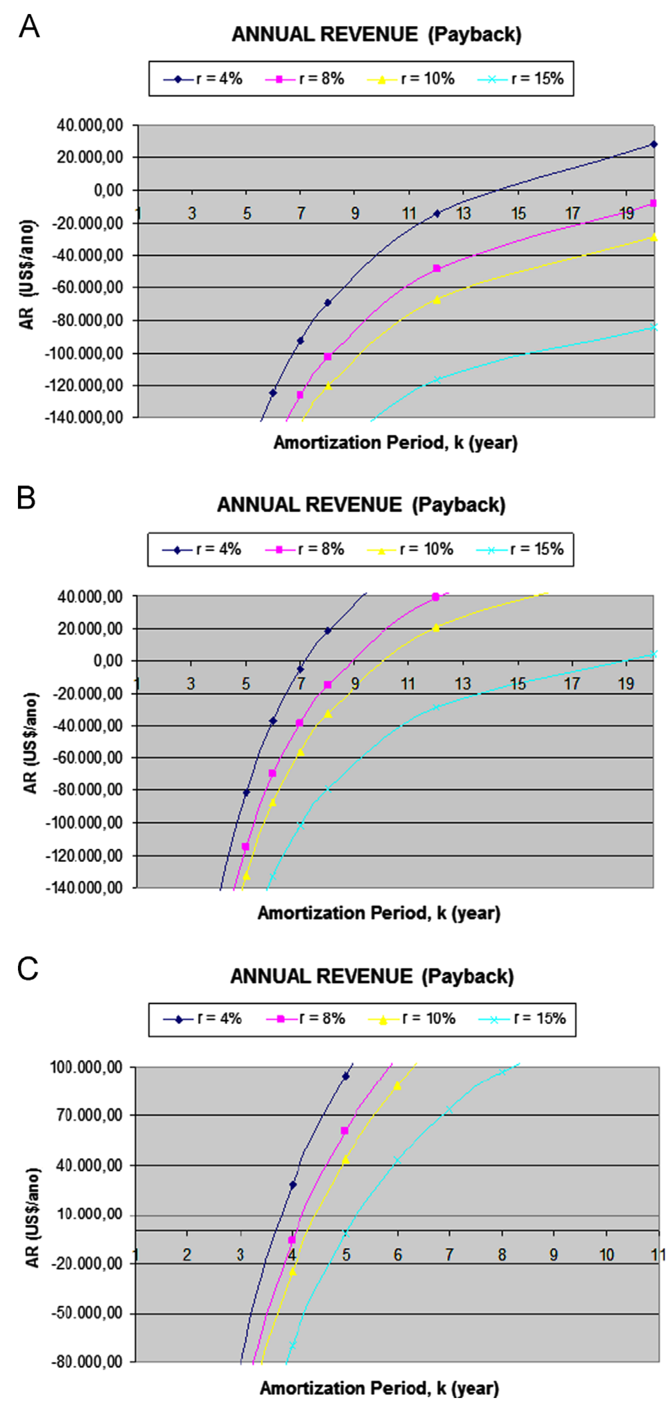

Fig. 11. Annual revenue (molar ratio 6:1, 8000 t/year, 8000 h/year). A: PV_{BIO}=2.194 R$/liter, PV_{GLY}=0 R$/kg, B: PV_{BIO}=2.211 R$/liter, PV_{GLY}=0 R$/kg, C: PV_{BIO}=2.246 R $/liter, PV_{GLY}=0 R$/kg.

variation of the investment when sale prices for biodiesel and glycerin vary. The annual revenue is calculated according to the sale of the produced glycerin. The calculation of the annual revenue considering the sale of glycerin is shown in Eq. (8). On the other hand, the calculation of the annual revenue without considering the sale of glycerin is shown in Eq. (9).

$$AR=(PV_{BIO}-C_{BIO})HY_{12.3}+(PV_{GLY}-C_{GLY})HY_{14.2} \quad (8)$$

$$AR=(PV_{BIO}-C_{BIO})HY_{12.3}-C_{GLY}HY_{14.2} \quad (9)$$

6. Conclusions

The study presented a proposal for calculating the cost of biodiesel and glycerin based on a thermoeconomic analysis incorporating the costs of CO_2 as carbon credits for biodiesel production plant of 8000 t of annual production with 8000 h of operation. The study included the calculation of specific physical and chemical exergy of flows in each stage of the plant, an exergy calculation of increments and the calculation of irreversibilities in each stage of the plant, as well as the overall system.

From the thermoeconomic analysis, it is possible to conclude that a lower MEC coincides with the lower value of irreversibility found in the system. This particular case is the one which has a reaction temperature of 60 °C, a molar ratio (methanol/oil) of 6:1 and a production of 8000 t of biodiesel per year with 8000 h of operation. The cost of biodiesel and glycerin, with an annual interest rate of 4% and an amortization period of 1 year was US$ 0.1401/kWh (1.33 US$/ liter) and 0.0269 US$/kWh (0.1422 US$/kg), respectively. To calculate the annual revenue, a selling price of biodiesel and glycerin ranging from 1.15 US$/liter to 1.1 US$/kg, was considered according to the prices in the Brazilian market in 2009 compared with the price of diesel and glycerin. Thus, the period of investment return (payback) was from the third year forth. Depending on the increase or decrease in the sale prices of both biodiesel and glycerin, the payback tends to significantly increase or decrease. It can be clearly seen in the figures in the previous chapter. It is evident that the sale of glycerin is of vital importance in order to reduce the selling price of biodiesel, getting the most profitable payback for the plant under study.

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